Astrometry of natural satellites Improving the dynamics of Jupiter, Mars and Saturn systems with old observations

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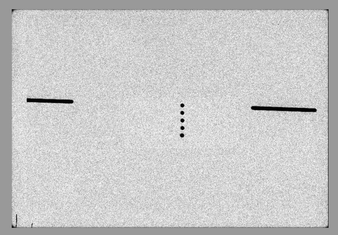
Abstract

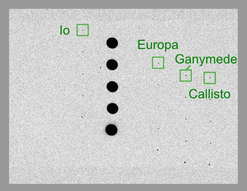
A new astrometric reduction of old photographic plates, benefiting from modern technologies such as sub-micrometric scanners associated with a reduction using accurate catalogues (UCAC at the present time and Gaia in a near future), provides improved knowledge of the orbital motion of planetary satellites. In the framework of an international collaboration first, and in the FP7 ESPaCE European project afterward, U.S. Naval Observatory plates were digitized with a new generation scanning machine of the Royal Observatory of Belgium. The procedure was applied to a few hundred photographic plates of the Galilean satellites covering the years 1967-1998, of the Martian satellites covering the years 1967-1997, and of the major Saturnian satellites covering the years 1974-1998.
We provide results with an accuracy better than 70 mas in (RA,Dec) positions of the Galilean moons, better than 60 mas in (RA,Dec) positions of the Martian satellites, and better than 100 mas in (RA,Dec) positions of the Saturnian moons. Since the positions of the planets may be deduced from the observed (RA,Dec) positions of their satellites, we can also assess the accuracy of the ephemerides of Jupiter, Mars and Saturn.

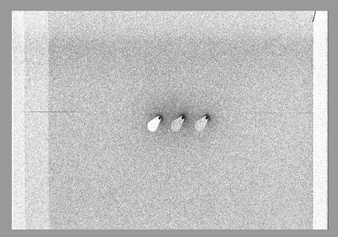
ESPaCE FP7 program and USNO photographic plates

The European Satellites Partnership for Computing Ephemerides ESPaCE project aims at strengthening the collaboration and at developing new knowledge, new technology, and products for the scientific community in the domains of the development of ephemerides and reference systems for natural satellites and spacecraft. The main European research centers involved in space sciences and dynamics contribute by combining their expertise. Their activities are focused on the extraction and analysis of astrometric data from space measurements not yet applied to the dynamics and to combine them with ground-based astrometric data.
We focus here on a subset of a few hundred photographic plates of the Galilean, Martian and Saturnian satellites, taken with the USNO 61-inch reflector (37’ field) and the USNO 26-inch refractor (57’ field) by D. Pascu (1977, 1979 & 1994) from 1967 to 1998. Each plate contains several exposures shifted either on the RA or the Dec axis. All these photographic plates were recently digitized with the new generation ROB digitizer (Robert et al., 2011, 2014).

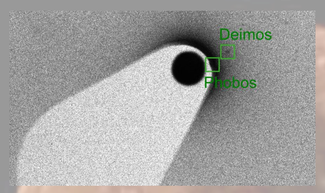


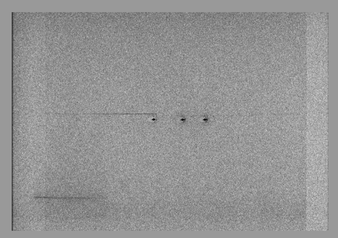
The USNO Galilean plate n°21014 and center



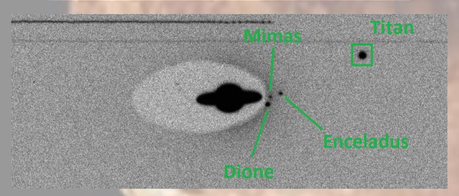


The USNO Martian plate n°11001 and center





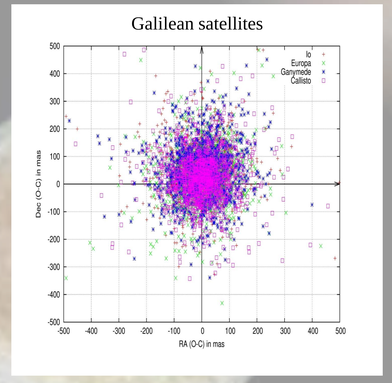
The USNO Saturnian plate n°23005 and center



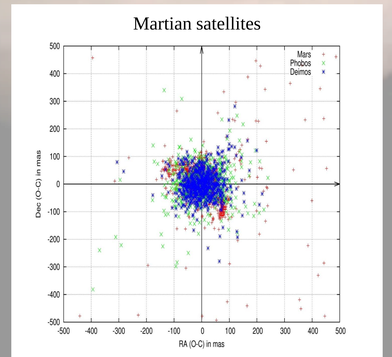
Analysis and astrometric reduction

The positions of the images of the planet, satellites and stars are extracted by means of a specific process including the use of the Source Extractor software (Bertin et al., 1996) and an IDL ellipse and limb fitting. The objects assumed to be present in the field are identified from existing catalogs to select only real astrometric sources. This process defines areas on the images in which the objects have to be found (Robert, 2011). All the available stars (depending on the catalog used) are identified and more, those that are not detected by eye. The obtained positions are finally corrected for the optical distortion introduced by the objective/camera unit during the digitization and for the instrumental coma-magnitude effect.
Astrometric (RA,Dec) results of the satellites and the planets are determined in an ICRS geocentric frame to be easily compared with the most recent satellite and planetary ephemerides.
Because of the few number of available stars, the astrometric reduction is quite different from a common astrometric process: the positions are calculated after correcting for instrumental and spherical effects that take into account the parallax and aberration effects and the total atmospheric refraction. (RA,Dec) positions are deduced from tangential apparent coordinates; only 4 parameters modeling the scale, orientation and center of field are fitted for a minimum of 2 reference stars. The contribution of each effect is separated.

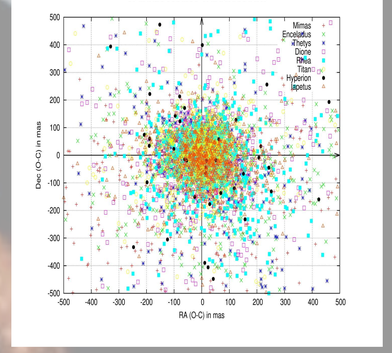
Galilean satellites



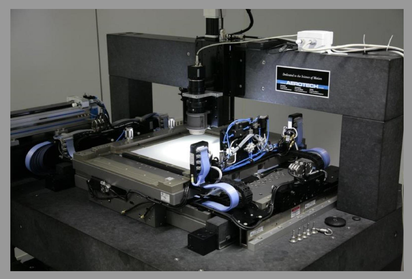
Martian satellites



Saturnian satellites



Sub-micrometric ROB digitizer



Galilean obs. (mas)	$\overline{(O-C)}_{acos\delta}$	$\overline{\sigma}_{acos\delta}$	$\overline{(O-C)}_{\delta}$	$\overline{\sigma}_{\delta}$
INPOP08	42,7	74,3	47,9	94,9
INPOP10	3,1	69,7	34,7	76,4
DE421	-1,3	70,1	39,0	77,6
DE430	-1,8	70,0	37,7	78,0

Martian obs. (mas)	$\overline{(O-C)}_{acos\delta}$	$\overline{\sigma}_{acos\delta}$	$\overline{(O-C)}_{\delta}$	$\overline{\sigma}_{\delta}$
INPOP08	2,3	59,8	2,6	57,8
INPOP10	3,2	59,8	2,8	57,8
DE421	2,3	59,7	2,7	57,8
DE430	2,6	59,7	2,7	57,8

Saturnian obs. (mas)	$\overline{(O-C)}_{acos\delta}$	$\overline{\sigma}_{acos\delta}$	$\overline{(O-C)}_{\delta}$	$\overline{\sigma}_{\delta}$
INPOP08	2,85	100,44	-11,21	99,09
INPOP10	2,82	101,07	-10,65	99,51
DE421	3,06	100,98	-10,61	99,47
DE430	3,09	100,88	-10,61	99,54

Astrometric results

The (O-C)s are for observations of the Galilean satellites first, then for Mars, Phobos and Deimos, and for the eight major Saturnian satellites. Positions are deduced from the measurements.
The plots show details of the (RA,Dec) (O-C)s according to the INPOP10 (Fienga et al., 2010) planetary ephemeris and IMCCE (Lainey et al., 2007, 2009, 2011) satellite ephemerides. The last Figure shows the sub-micrometric ROB digitizer used for the digitization. Tables compare the averages of the Galilean, Martian and Saturnian (RA,Dec) (O-C)s and rms residuals respectively, in mas, according to the INPOP08 (Fienga et al., 2008), INPOP10, DE421 and DE430 (Folkner et al., 2008, 2014)) planetary ephemerides.

Conclusion

We demonstrated the high interest to continue the analysis of old photographic plates such as USNO’s. Thanks to the new technologies, we were able to provide astrometric data with a high accuracy after applying the necessary corrections. We now provide an accuracy about of 70 mas (~210 km) for (RA,Dec) positions of the planet Jupiter and its moons, 60 mas (~18 km) for (RA,Dec) positions of the planet Mars and its satellites, and 100 mas (~700 km) for (RA,Dec) positions of the planet Saturn and its satellites. Note that the previous accuracy was up to 200 mas and only for relative positions. More important, these results indicate that we now can reach an accuracy better than that of CCD observations (Colas et al., 1991) and as good as the old spacecraft measurements of the Martian system for example. These results encourage us to continue the analysis of old photograhic plates. The steps after will be to reduce other relevant old photographic plates such as Yale Southern Station Saturnian observations, and to continue the effort in reducing old observations. Old CCD observations could also be re-reduced in the same scope, increasing the accuracy of these data.

To fullfill our program, we have started the NAROO project (New Astrometric Reduction of Old Observations) of the IMCCE – Paris Observatory, A new sub-micrometric machine will be set up in France to digitize several thousands photographic plates for astrometry and thus dynamics purposes. Moreover, the Gaia astrometric catalog of reference stars will provide proper motions of sources up to mag 18 with an accuracy better than 6 mas over one century. We look forward its arrival which will be be a revolution in Solar System astrometry: reductions of old observations will yield increase accuracy by eliminating errors due to "old" reference star catalogs. We will be able to observe in the past with today accuracy, that is essential for fast moving objects of the Solar System.

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